A PRELIMINARY VISUAL ORBIT OF BY DRACONIS

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ABSTRACT

We report on the preliminary determination of the visual orbit of the double-lined spectroscopic binary system BY Draconis with data obtained by the Palomar Testbed Interferometer in 1999. BY Dra is a nearly equal-mass double-lined binary system whose spectroscopic orbit is well known. We have estimated the visual orbit of BY Dra from our interferometric visibility data fit both separately and in conjunction with archival radial velocity data. Our BY Dra orbit is in good agreement with the spectroscopic results. Due to the orbit's face-on orientation, the physical parameters implied by a combined fit to our visibility data and radial velocity data do not yet result in precise component masses and a system distance, but with continued interferometric monitoring we hope to improve the mass estimates to better than 10% determinations.

Subject headings: binaries: spectroscopic — binaries: visual — stars: flare — stars: individual (BY Draconis) — techniques: interferometric

1. INTRODUCTION

BY Draconis (HDE 234677, Gl 719) is a well-studied, nearby (~ 15 pc), multiple stellar system containing at least three objects. The A and B components form a short-period (6 day) late-type (K6 Ve–K7 Vvar) binary system, whose spectroscopic orbit is well known (Bopp & Evans 1973, hereafter BE73; Vogt & Fekel 1979, hereafter VF79; Lucke & Mayor 1980, hereafter LM80). BY Dra is the prototype of a class of late-type flare stars characterized by photometric variability due to star spots; rapid rotation; and Ca II, H, and K emission lines. Like the BY Dra system itself, a large fraction ($>85\%$) (Bopp & Fekel 1977; Bopp, Noah, & Klimke 1980) of BY Dra stars are known to be in short-period binary orbits. The rapid rotation of BY Dra A (period 3.83 days) that gives rise to the spotting and photometric variability is consistent with pseudosynchronous rotation with the A-B orbital motion (Hut 1981; Hall 1986), but pseudosynchronization is disputed by Glebocki & Stawikowski (1995, 1997), who assert asynchronous rotation and roughly 30° misalignment of the orbital/rotational angular momentum vectors.

Despite the fact that the BY Dra A and B components are nearly equal mass, the system exhibits a significant brightness asymmetry in spectroscopic studies (VF79; LM80). VF79 attributes this to the hypothesis that A and B components of BY Dra are pre–main-sequence objects (VF79; Bopp et al. 1980) and are still in the contraction phase. VF79 argues for physical sizes of the A component in the range of 0.9–1.4 $R_\odot$, based primarily on rotation period and $v \sin i$ considerations. LM80 concur with the A component physical size argument from their $v \sin i$ measurements, estimating a 1.2 $R_\odot$ size for a $\sin i \approx 0.5$ (presuming rotation/orbit spin alignment with pseudosynchronization and our orbital inclination from Table 2). However, they continue by pointing out that if the A component macroturbulence were significantly larger than solar, then the $v \sin i$ measurements and the component diameters they are based on are biased high. If the pre–main-sequence interpretation is correct, the BY Dra components are additionally interesting as examples of the transition region between pre– and zero-age main-sequence states.

BY Dra was detected as a hierarchical triple system through common proper-motion measurements of a BY Dra C component by Zuckerman et al. (1997); they find the C component separated by 17″ from the A-B pair. Zuckerman's photometry on the C component is consistent with an M5 main-sequence interpretation ($V - K \approx 6.2$); assuming all three stars are coeval, this clearly poses problems for the VF79 pre–main-sequence hypothesis for the A and B components. At a projected physical separation of approximately 260 AU from the A-B binary, the putative low-mass C component would have negligible dynamical influence on the A-B binary motion. Further, the *Hipparcos* catalog (ESA 1997) implies the presence of at least one additional component as it lists BY Dra as having a circular photocentric orbital solution with a 114 day period. This 114 day period is previously unreported in spectroscopic studies, and if correct it is difficult to understand why this motion was not previously detected.

Herein we report on a preliminary determination of the BY Dra A-B system visual orbit from near-infrared, long-baseline interferometric measurements taken with the Palomar Testbed Interferometer (PTI). PTI is a 110 m *H*- (1.6 μm) and *K*-band (2.2 μm) interferometer located at Palomar Observatory and described in detail elsewhere (Colavita et al. 1999). PTI has a minimum fringe spacing of roughly 4 mas in the *K*-band at the sky position of BY Dra, allowing resolution of the A-B binary system.

2. OBSERVATIONS

The interferometric observable used for these measurements is the fringe contrast or *visibility* (squared, V^2) of an observed brightness distribution on the sky. The reader is referred to one of the previous papers in this series (Boden et al. 1999a, 1999b; Boden, Creech-Eakman, & Queloz 2000) for descriptions of the V^2 observables for binary stars.

BY Dra was observed in conjunction with objects in our calibrator list (Table 1) by PTI in *K*-band ($\lambda \sim 2.2$ μm) on 21 nights between 1999 23 June and 21 October, covering roughly 20 periods of the system. Additionally, BY Dra was

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TABLE 1
PTI BY DRA CALIBRATION OBJECTS CONSIDERED IN OUR ANALYSIS

Object Name	Spectral Type	Star Magnitude	BY Dra Separation (deg)	Adopted Model Diameter (mas)
HD 177196......	A7 V	5.0 V/4.5 K	6.6	0.70 ± 0.06
HD 185395......	F4 V	4.5 V/3.5 K	9.9	0.84 ± 0.04

NOTE.—The relevant parameters for our two calibration objects are summarized. The apparent diameter values are determined from effective temperature and bolometric flux estimates based on archival broadband photometry and visibility measurements with PTI.

observed by PTI in H-band ($\lambda \sim 1.6$ μm) on 1999 13 September, 2 October, and 20 October. BY Dra, along with calibration objects, was observed multiple times during each of these nights, and each observation, or scan, was approximately 130 s long. For each scan we computed a mean V^2 value from the scan data and the error in the V^2 estimate from the rms internal scatter. BY Dra was always observed in combination with one or more calibration sources within $\sim 10°$ on the sky. Table 1 lists the relevant physical parameters for the calibration objects. We have calibrated the V^2 data by methods discussed in Boden et al. (1998). Our 1999 observations of BY Dra result in 67 calibrated visibility measurements (50 in K band, 17 in H band). One notable aspect of our BY Dra observations is that its high declination (51°) relative to our Palomar site (33° latitude) puts it at the extreme northern edge of the delay line range on our north-south baseline (Colavita et al. 1999), implying extremely limited $u-v$ coverage on BY Dra. To our PTI visibilities we have added 44 double-lined radial velocity measurements: 14 from BE73, seven from VF79, and 23 CORAVEL measurements from LM80.
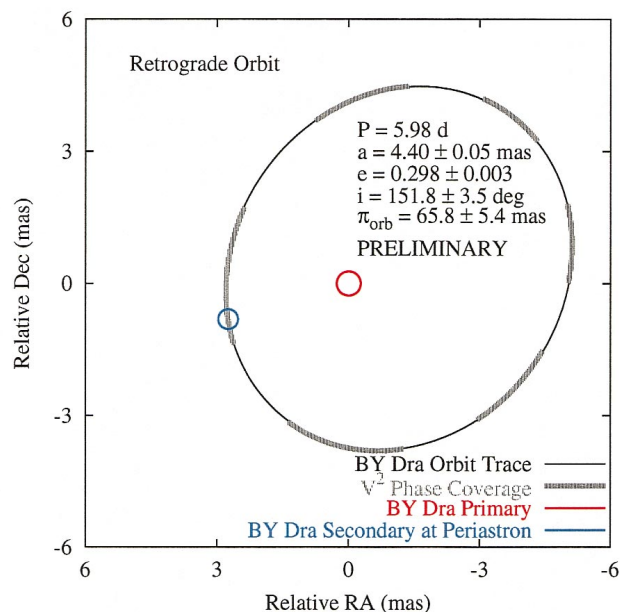

FIG. 1.—Visual orbit of BY Dra. The relative visual orbit model of BY Dra is shown, with the primary and secondary objects rendered at T_0 (periastron). The heavy lines along the relative orbit indicate areas where we have orbital phase coverage in our PTI data (they are not separation vector estimates); our data samples most phases of the orbit well, leading to a reliable orbit determination. Component diameter values are estimated (see discussion in § 5) and are rendered to scale.
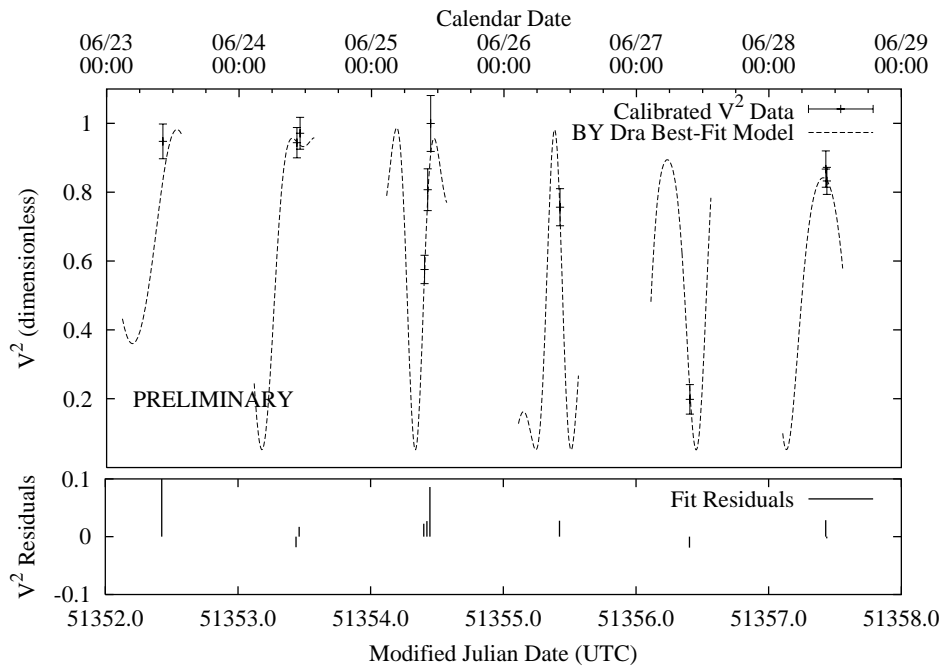
3. ORBIT DETERMINATION

As in previous papers in this series (Boden et al. 1999a, 1999b, 2000), the estimation of the BY Dra visual orbit is made by fitting a Keplerian orbit model directly to the calibrated (narrowband and synthetic wideband) V^2 and RV data on BY Dra; because of the limited $u-v$ coverage in our data, derivation of intermediate separation vector models is impossible. The fit is nonlinear in the Keplerian orbital elements and is therefore performed by nonlinear least-squares methods with a parallel exhaustive search strategy to determine the global minimum in the χ^2 manifold. The reader is referred to the previous papers for further details on our orbit estimation procedures.

Figure 1 depicts the relative visual orbit of the BY Dra system, with the primary component rendered at the origin and the secondary component rendered at periastron. We have indicated the phase coverage of our V^2 data on the relative orbit with heavy lines; our data samples most phases of the orbit well, leading to a reliable orbit determination. The apparent inclination is very near the estimate given by VF79 based on the primary rotation period, assumed size, and assumption of parallel orbital/rotational angular momentum alignment. The orbit is seen approximately 30° from a face-on perspective, which makes physical parameter determination difficult (§ 5).

Figure 2 illustrates comparisons between our PTI V^2 and archival RV data and our orbit model. In Figure 2a, six consecutive nights of K-band visibility data and visibility predictions from the best-fit model are shown, inset with fit residuals along the bottom. That there are only 1–3 data points in each of the nights follows from the brief time each night that BY Dra is simultaneously within both delay and zenith angle limits. Figure 2b gives the phased archival RV data and model predictions, inset with a histogram of RV fit residuals. The fit quality is consistent with previous PTI orbit analyses.

Spectroscopic orbit parameters (from VF79 and LM80) and our visual and spectroscopic orbit parameters of the BY Dra system are summarized in Table 2. We give the results of separate fits to only our V^2 data (our "V^2-only Fit" solution) and a simultaneous fit to our V^2 data and the archival double-lined radial velocities—both with component diameters constrained as noted above. All uncertainties in parameters are quoted at the 1 σ level. We see good statistical agreement between all the derived orbital parameters with the exception of the LM80 period estimate.

4. COMPARISONS WITH HIPPARCOS MODEL

The Hipparcos catalog lists a circular photocentric orbital solution for BY Dra with a 114 day period (ESA 1997), presumably in addition to the well-established 6 day period A-B motion. As noted above it is difficult to
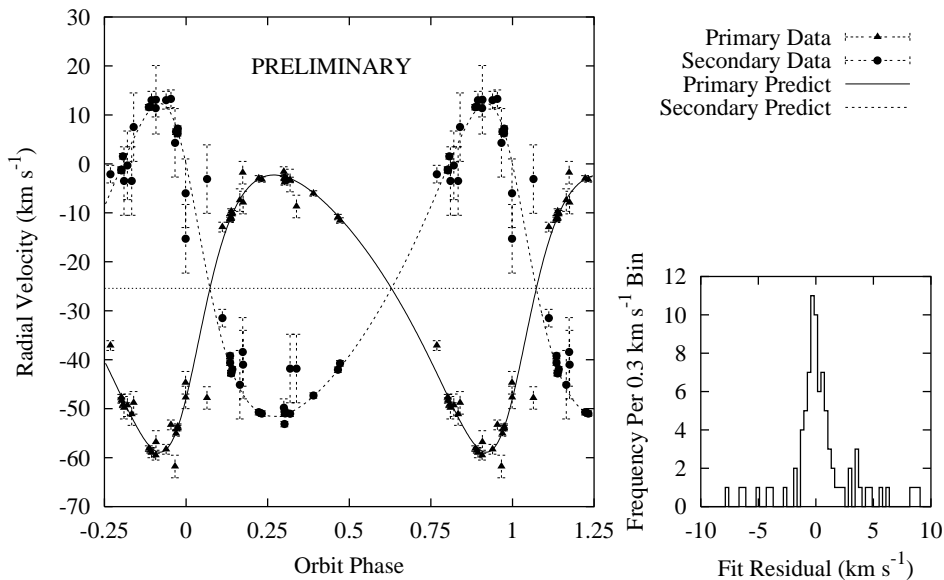
Fig. 2a

Fig. 2b

Fig. 2.—Joint V^2/radial velocity fit of BY Dra. (a) Six consecutive nights of V^2 data on BY Dra and best-fit model predictions. (b) Phased archival RV data (BE73; VF79; LM80) and RV predictions from our best-fit orbital model. Inset is a histogram of RV residuals to the fit model.

reconcile this hypothesis with the quality of the existing short-period spectroscopic orbit solutions from VF79 and LM80. However, if the A-B system indeed did have a companion with this period, unlike BY Dra C it would lie within PTI's 1″ primary beam, and if sufficiently luminous it would bias the visibility measurements used in our BY Dra A-B visual orbit model. We see no indications of this in our orbital solutions; the quality of our BY Dra visual orbit solution is consistent with our results on other systems. But it remains possible we have misinterpreted our V^2 data in the binary star model fit, and we are motivated to consider the 114 day periodicity hypothesis in the archival RV data.

We note that the *Hipparcos* model is a photocentric orbit and therefore calls for the A-B system to exhibit a reflex

motion with radius ≥ 0.05 AU at the putative distance of BY Dra. The 114 day orbit hypothesis is at high inclination (113°) and therefore would produce a radial velocity semi-amplitude for the A-B system barycenter ≥ 3.95 km s^{-1}. This value is large compared to fit residuals observed by VF79 and LM80 in their spectroscopic orbital solutions (and by ourselves in the joint fit with our visibilities; Table 2), suggesting the 114 day motion hypothesis is unlikely.

To quantify this issue we have considered Lomb-Scargle periodogram analyses of the LM80 BY Dra radial velocity data. We have chosen to use the LM80 data because it is the more precise sample, yielding an rms residual of roughly 0.5 km s^{-1} in our A-B orbit analysis. Figure 3 gives periodograms of the LM80 primary and secondary radial velocity

TABLE 2

ORBITAL PARAMETERS FOR BY DRA

ORBITAL PARAMETER	VF79	LM80	PTI 99 V^2-only Fit	PTI 99 Full Fit
Period (days)	$5.9750998 \pm 8.7 \times 10^{-5}$	$5.975112 \pm 8.2 \times 10^{-6}$	5.975078	$5.975078 \pm 1.0 \times 10^{-5}$
T_0 (MJD)	41146.59 ± 0.07	43794.193 ± 0.023	51376.1407 ± 0.0087	51376.1232 ± 0.0045
e	0.36 ± 0.03	0.3066 ± 0.0063	0.321 ± 0.015	0.2978 ± 0.0032
K_1 (km s^{-1})	28.2 ± 1.0	28.55 ± 0.25		28.31 ± 0.14
K_2 (km s^{-1})	28.8 ± 1.8	32.04 ± 0.35		31.96 ± 0.15
γ (km s^{-1})	-24.47 ± 0.65	-25.35 ± 0.14		-25.431 ± 0.078
ω_1 (deg)	220 ± 5	229.3 ± 1.3	240.7 ± 8.2	232.21 ± 0.91
Ω_1 (deg)			106.7 ± 8.9	115.1 ± 1.3
i (deg).................			153.0 ± 3.6	151.8 ± 3.5
a (mas)			4.376 ± 0.056	4.399 ± 0.050
ΔK_{CIT}			0.69 ± 0.11	0.571 ± 0.061
ΔH_{CIT}			1.39 ± 0.30	0.92 ± 0.24
ΔV		1.15 ± 0.1		
χ^2/dof................			1.1	2.4 (1.5 V^2/3.6 RV)
$\overline{|R_{V^2}|}$			0.033	0.038
$\overline{|R_{RV}|}$ (km s^{-1})		0.55		2.3 (0.49 COR)

NOTE.—Summarized here are the apparent orbital parameters for the BY Dra system as determined by VF79, LM80, and PTI. We give two separate fits to our data, with and without including archival double-lined radial velocities in the fit. Quantities given in italics are constrained to the listed values in our model fits. We have quoted the longitude of the ascending node parameter (Ω) as the angle between local east and the orbital line of nodes measured positive in the direction of local north. Due to the degeneracy in our V^2 observable, there is a 180° ambiguity in Ω; by convention we quote it in the interval of [0,180). We quote mean absolute V^2 and RV residuals in the fits, $\overline{|R_{V^2}|}$ and $\overline{|R_{RV}|}$, respectively.

data. First, Figure 3a gives a periodogram of the primary and secondary RV data, with probability of false alarm levels (P_{fa}) as noted. As expected, both component lines exhibit a significant periodicity at the observed A-B orbit frequency of approximately (6 days)$^{-1}$ (indicated by the vertical line). In the same plot, we sample the frequency of the 114 day orbit hypothesis, and no comparable periodicity is evident on the scale of the A-B motion.

Presuming the 114 day motion hypothesis might be superimposed on the 6 day A-B orbit, in Figure 3b we give a
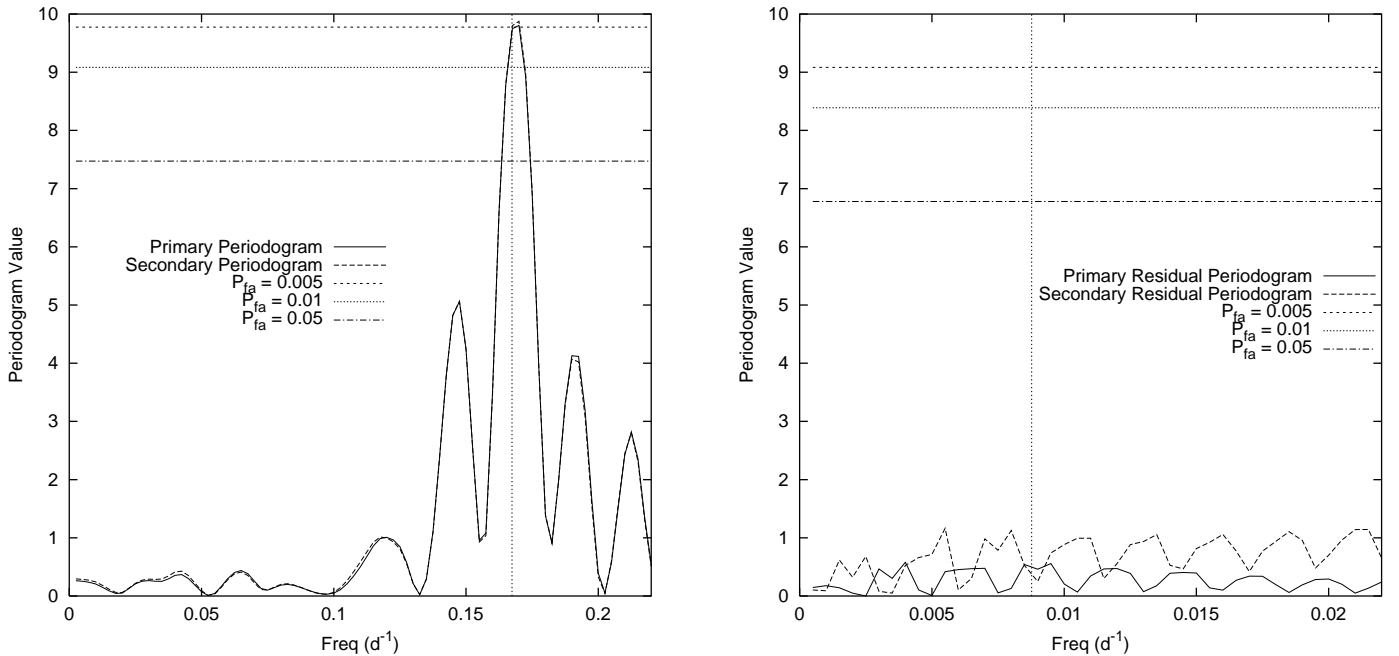

FIG. 3.—Lomb-Scargle periodograms on LM80 BY Dra radial velocity data. To assess the 114 day orbit hypothesis for an additional companion to the BY Dra A-B system, we have performed Lomb-Scargle periodogram analysis on double-lined BY Dra data from LM80. *Left*: Standard periodograms on primary and secondary RV data from the LM80 data set. Statistically significant response is seen at the well-known 6 day A-B period (*vertical line*). *Right*: Low-frequency periodogram of the residuals of the LM80 data to the best-fit A-B orbit model. No significant response is evident at the putative 114 day period (*vertical line*).

periodogram of the LM80 primary and secondary RV fit residuals to the 6 day hypothesis fit. In Figure 3b we have adjusted to range of the periodogram to finely sample the frequency range around the $(114 \text{ days})^{-1}$ hypothesis (indicated by the vertical line). No significant periodicity is noted at this or any other frequency. The LM80 RV data set spans roughly 400 days, so a 4 km s^{-1} amplitude periodicity in this data set should have been evident in our analysis. Given these considerations, it seems unlikely that our V^2 measurements and A-B orbit model are affected by the presence of a third luminous body.

5. DISCUSSION

The combination of the double-lined spectroscopic orbit and relative visual orbit allow us to estimate the BY Dra A-B component masses and system distance. However, because of the nearly face-on geometry of the A-B orbit, the accuracy of our inclination estimate, and consequently the component mass estimates and system distance estimate, is relatively poor. The low-inclination geometry is particularly difficult for astrometric studies because the astrometric observable (V^2 in this case) becomes highly insensitive to small changes in the inclination Euler angle. Table 3 lists the physical parameters we estimate from our full-fit orbit solution. The mass estimates are in a reasonable range for stars of this type but are formally crude—roughly 24% 1 σ uncertainties, as is the system distance estimate—roughly 8% 1 σ. In both cases the dominant error is the inclination; to improve these mass and distance estimates by a factor of 2, we must improve the inclination estimate by a factor of 2. The orbital parallax with its large error is in 1 σ agreement with the *Hipparcos* trigonometric determination of 60.9 ± 0.75 mas, but we note that the *Hipparcos* solution was derived jointly with the 3 mas, 114 day orbital hypothesis that we believe to be suspect (§ 4).

Table 3 also gives component absolute magnitudes and $V - K$ color indices derived from archival broadband photometry, our H- and K-component relative magnitudes, the LM80 V relative magnitude, and our system distance estimate. The component color indices are unaffected by errors in the system distance and seem to be in good agreement with the color indices expected from stars in this mass range and the classical spectral typing of the BY Dra system. The absolute magnitudes are somewhat uncertain from the relatively poor distance estimate but suggest a modest discrepancy with the mass-luminosity models of Baraffe et al. (1998, hereafter BCAH98). As depicted in Figure 4, both

components appear roughly 0.5–1 mag brighter at V and K than the BCAH98 models evaluated at our model masses would predict. The cause for this discrepancy could be abnormally large component sizes suggested by VF79, or the component masses are underestimated in our analysis. Clearly, we need to improve our orbit model so as to further constrain the BY Dra component parameters.

To assess the VF79 component size/pre–main-sequence hypothesis, the most interesting measurement of the BY Dra A-B system would be unequivocal measurements of the component diameters. Unfortunately, our V^2 data are as yet insufficient to determine these diameters independently. Canonical sizes of 1.0 and 0.8 $R_\odot$ (indicated by model effective temperatures and our IR flux ratios) yield angular diameters of approximately 0.6 and 0.5 mas for the A and B components, respectively. At these sizes neither the H- nor K-band fringe spacings of PTI sufficiently resolve the components to independently determine component sizes. Consequently, we have constrained our orbital solutions to these 0.6 and 0.5 mas model values. Our data does in fact prefer the slightly smaller primary component diameter to the larger 1.2 $R_\odot$ size implied by VF79 and LM80 $v \sin i$ and rotational period measurements. However, either primary model diameter is possible with the expected systematic V^2 calibration errors. Additional data we will collect in the coming year (see below) may well place interesting upper limits on the component sizes, but unambiguous resolution of the BY Dra A and B components will have to wait for a longer baseline infrared interferometer, most likely the CHARA array currently under construction on Mount Wilson.[4]

The prospects for improving the BY Dra orbital model in general and the orbital inclination estimate in particular are reasonable. To achieve 10% mass determinations on the BY Dra components, we will need to reduce the inclination uncertainty to approximately 1°.5, which implies a rough quadrupling of the PTI visibility data on BY Dra or an improvement of our V^2 measurement precision by a factor of 2 on a data set of similar size to that already collected. Both are plausible; PTI is expected to be in normal operation for at least another season, and hardware upgrades to the PTI fringe camera are planned and should provide significant improvements in sensitivity.

[4] http://www.chara.gsu.edu/CHARA/array.html.

TABLE 3

PHYSICAL PARAMETERS FOR BY DRA

Physical Parameter	Primary Component	Secondary Component
a (10^{-2} AU)................	3.14 ± 0.36	3.55 ± 0.41
Mass ($M_\odot$)	0.59 ± 0.14	0.52 ± 0.13
System distance (pc)........	15.2 ± 1.2	
π_{orb} (mas)	65.8 ± 5.4	
Model diameter (mas)......	$0.60 (\pm 0.06)^*$	$0.50 (\pm 0.05)^*$
M_K (mag)....................	4.47 ± 0.18	5.04 ± 0.18
M_H (mag)...................	4.48 ± 0.21	5.40 ± 0.29
M_V (mag)...................	7.48 ± 0.18	8.63 ± 0.18
$V - K$ (mag)................	3.019 ± 0.039	3.598 ± 0.061

NOTE.—Summarized here are the physical parameters for the BY Dra A-B system as derived primarily from the full-fit solution orbital parameters in Table 2.
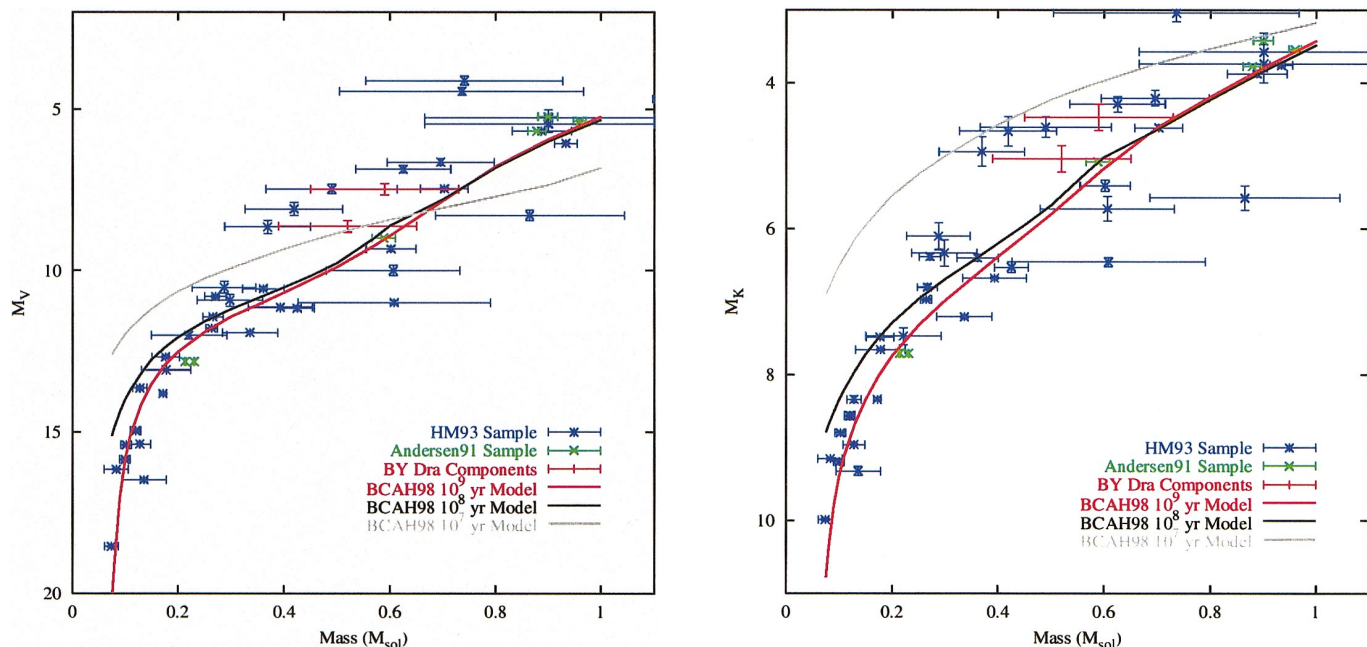*Constrained to the listed values in our model fits.

FIG. 4.—BY Dra components in mass/luminosity space. Here we give the positions of the A and B BY Dra components in observable mass/M_V (*upper panel*) and mass/M_K (*lower panel*) spaces (an emulation of Fig. 3 from BCAH98), superimposing low-mass objects from Henry & McCarthy (1993) and Andersen (1991) and BCAH98 solar-metallicity model tracks at ages of 10^9, 10^8, and 10^7 yr. While our mass determinations are currently too crude to be definitive, both components appear overluminous compared to the BCAH98 models, and it is difficult to reconcile the deviations with age effects.

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